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NAVORD REPORT 2766

THE NOL FRAGMENT VELOCITY RANGE

2 FEBRUARY 1953

U. S. NAVAL ORDNANCE LABORATORY

WHITE OAK, MARYLAND

NAVORD Report 2766

THE NOL FRAGMENT VELOCITY RANGE

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ABSTRACT: The development of the NOL fragment velocity range is reported. This range uses a rotating drum camera to record the passage of fragments past three lighted slits. The motion of the camera drum is such that the film moves parallel to the trajectory of the fragments. The sharp images of each fragment permit easy calculation of its velocity. This velocity depends upon a known fragment path defined by the geometry of the range and time of transit between slits which is determined by speed of film and spacing of successive fragment images on the film. The accuracy of the range is on the order of 1 to 2 per cent. The limitations of the range are discussed and further developments are suggested.

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White Oak, Maryland

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The work presented in this report was undertaken for the purpose of improving an existing photographic method of determining fragment velocities from exploding cases. Such information is necessary in the design of fragmentation projectiles. The work has been performed under Task NOL-Re2c-35-1-53. It may serve as guides to further research and design of ranges for other purposes.

The authors wish to acknowledge the assistance of N. Shapiro who derived the method of data reduction, and of F. J. Hemmer and James Schneider who assisted in the experimental work.

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By direction

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INTRODUCTION

1. Fragment velocity is an important parameter to be measured in the study of exploding shells. Considerable effort has been spent in developing means to obtain accurate velocity determinations for sufficiently large groups of fragments to represent this overall shell characteristic. Several methods for obtaining these data are available and are in use at different locations.

2. The prima-cord shutter, reference (a), and flash radiographic techniques, reference (b), have both been used to predict velocities by a displacement measurement at the shell. The screen chronograph, reference (c), and multi-station spark photographic methods, reference (d), give direct velocities, but the sampling is small and restricted to the fastest fragments of the group. High speed movie cameras with scintillating screens, references (e) and (f), give mean velocities directly for a large number of fragments over the entire trajectory which must be fairly long to assure reasonable accuracy. The rotating drum streak camera, reference (g), can be adapted to measure velocities of a large number of fragments with reasonable accuracy at some fixed distance from the exploding case, reference (h).

3. Initially the fragment velocity range at NOL was designed to duplicate the Bragg-Messerly rotating-drum camera shadowgraph method used at ERL, Bruceton, Pennsylvania. (The Bruceton cameras are being used in this range). This system, however, was not entirely satisfactory. As an improvement, a multi-slit object-image velocity matching system has been devised which utilizes the geometrical system already available and produces increased clarity of the records. With increased definition it was expected that additional information not previously attained from fragment velocity data would be available, viz: (a) observation of rotational motion of fragments in flight, (b) reasonable estimates of presented areas, and (c) measurements of retardations of groups of fragments. Although this information has not been obtained quantitatively, the increased resolution has made it possible to record more fragments with higher accuracy and readability. This report describes the developments of the NOL range and discusses further possible improvements.

DESIGN OF VELOCITY RANGE

4. <u>The Original Range, ERL Design.</u> The ERL-type velocity range is shown in Figure 1. As it was originally used, a limited beam of fragments from the shell came through the aperture in the bombproof wall in essentially a horizontal plane and passed between the camera and the slit box. With end initiation, the shell axis was oriented 5 degrees off vertical to compensate for the forward set of the fragment beam with respect to the plane normal to the case axis. The slit box consisted of three equally-spaced slits inclined at 45 degrees. At the time of firing, each slit was lighted by photoflash bulbs. A 7 inch focal length lens and a 2 inch totally reflecting prism were used in the camera to form an image of the slit box on the inner surface of the film drum in such a manner that the film moved effectively perpendicular to the fragment trajectory. The resulting record consisted of a continuous streak image of three bands of light, corresponding to the slits, in which the fragments appeared as shadows. Adjustment of slit width and lens aperture gave the proper contrast between fragments and background for the light source used.

5. Figure 1 also includes a record made with this system. Distance along the length of the film between the three images gave a measure of time of transit between the slits, while the image position within each light band was used to obtain path distance in the vertical plane defined by the fragment's trajectory. The geometry of the range was such that for any allowed trajectory this observed path length between outside slits deviated by less than 2 per cent from the true path length. Thus, with proper multiplying factors, the velocity of each fragment could be calculated from the record. The principal limitations to the accuracy of the result was the 2 per cent figure given above and the proper choice of center of mass of each image. The principal limitation of the range was the relatively low quality of record obtained since the fragments were hard to identify. A complete description of the system is given in reference (h).

6. <u>Change in Method of Slit Illumination.</u> The initial modification in the ERL range at NOL was to use commercial flash tubes as light sources instead of photoflash bulbs. The advantages were: (a) more uniform illumination over the entire slit length, (b) elimination of the necessity of replacing bulbs after each shot, and (c) increased reproducibility in light initiation. On the basis of previous investigation, reference (i), the G.E. FT-422 was selected. This

tube, with a light length of 18 inches and a diameter of 0.5 inches, employes Xenon as the discharge medium and has a maximum energy input at 2000 volts of 480 watt-seconds. At the present time, these tubes, each operated from a 3000 microfarad capacitor bank at 480 volts, are triggered by approximately a 12,000 volt pulse which is applied to a third electrode foil wrapping along the length of the tube. By proper placement of the foil on the tube, it also serves effectively as a reflector. The lowered voltage and increased charge capacity applied to the tubes produces lowered peak intensity of light with longer duration. Such an arrangement was required since reasonably intense light for several milliseconds is needed in this application. The value of 480 volts was selected because electrolytic capacitors having large capacities with voltage ratings up to 480 volts were readily available.

7. Modification to Result in Matching of Object and Image Travel. Because of an obvious need to improve the definition of the fragment images on the film, some modification of the ERL method was sought. This was attained without changing the geometry of the range by utilizing a completely different optical principle. The film is moved in a plane parallel with the fragment trajectory, making it possible, by adjusting the rate of rotation of the drum, to match the film speed to the mean fragment speed. The fragments are essentially motionless relative to the film, and sharp images result for short exposures. A slit placed perpendicular to the fragment trajectory to limit the exposure time results in an image of the fragment recorded with its orientation in a plane perpendicular to the optical axis of the camera at the time it passed the slit. Such an image is marked improvement over the smeared image produced by the ERL system where the fragment moves with a high velocity relative to the film. Several slits used in this arrangement can be used to compute the velocity of each fragment.

8. With exact matching of film-fragment speeds and a horizontal fragment trajectory, the images made as the fragment passed each slit would coincide. If the speeds match, but the trajectory is not horizontal, the images will be in a straight line perpendicular to the length of the film. If the velocity matching is not exact, the successive images will extend along the length of the film. Exact matching is possible only for a few fragments; some fragments will be too fast and some too slow. The image pattern produced on the film by a slow fragment would be just the reverse of that produced by a fast fragment. By spacing the slits unequally, one can determine from the records if the fragments are slower or faster than the matching speed. Figure 3 shows the general arrangement of the system and a typical record.

9. Illumination of Fragments. With the object-image velocity matching system, the possibility of either front lighting or back lighting of fragments exists. For front lighting the slit arrangement is placed between the fragment beam and the camera, and lights are directed onto the fragment beam such that the fragments would reflect light back to the camera as they passed the slits. For back lighting the camera takes a continuous picture of lighted slits and the passage of fragments between the camera and slits produces silhouette images of the fragments on the film. Front lighting, if practical, would have definite advantages. An almost unlimited number of slits could be used so that decelerations as well as velocities could be obtained. The images would also give better indication of the rotation of fragments in flight.

10. Both methods of illumination were tried. Because of the poor reflectivity of the fragments, the front lighting scheme was not satisfactory. Figure 4(a) shows a typical record for this method of illumination. The record was taken with an f/8 aperture opening on Super XX film. The effective slit width at the fragments was on the order of 0.5 inches. The fragments were illuminated by three FT-422 flash tubes driven from a peak voltage of 2000 volts. The contrast is good, but the definition is too poor for the record to be usable. Only by decreasing slit width and aperture opening could the resolution be improved. It was believed that a many-fold increase in light intensity would be required to permit proper adjustments for resolution. The improvements to be expected were not considered worth the effort required to obtain them.

11. Figure 4(b) shows a typical record obtained with the back lighting shadow technique of illumination. This record was taken at an aperture opening of f/32 on Super XX film with slit widths of approximately 0.026 inches and the flash tubes energized at a peak voltage of 480 volts. Both resolution and contrast are satisfactory. Because the camera records overlapping images of the lighted slits, the range is limited to three or so slits. Additional slits would also reduce the contrast. Velocities, however, can be measured, and this lighting technique has been adopted.

12. Camera. The original range was designed with a magnification factor of approximately 1:30 for the camera. The records for this arrangement were always hard to use: the images of small fragments were hard to identify and highly precise measurements were required to insure reasonable accuracy of the results. Changing to the object-film velocity matching technique permitted use of a larger magnification factor, and a new lens giving magnification of approximately 1:15 was incorporated into the camera.

13. Reasonable matching of object and film velocities resulted with the original 30 rps drum speed and the magnification factor of 1:30. An increase in the magnification factor produced considerable mismatch of velocities with the film velocity slower than the object velocity. Thus, the images of the fragments were spread out on the film, making identification more difficult. Further, the potential accuracy of measuring fragment velocities was reduced. A measure of the accuracy is given by:

$$\frac{\Delta V_o}{V_o} = -\frac{1}{S}\left(\frac{V_o}{V_i}\right)\Delta d,$$

where V_o is fragment velocity, V_i is film velocity, S is slit separation seen by the film and d is the horizontal distance between images of the fragment made in passing the slits. Any change to increase (V_o/V_i) will tend to decrease accuracy. This is what the increase in magnification factor does. A 60 rps motor has been substituted for the 30 rps motor to drive the drum. This gives matching of velocities for fragment speeds on the order of 3000 feet per second. The records can be read satisfactorily for fragment velocities up to twice this value. Higher drum speeds would be required if the range were used predominantly to observe extremely high speed fragments.

14. With a fixed light intensity, the lens aperture and slit width can be adjusted to produce optimum records. This consists mainly of getting proper contrast of both single shadows and overlapping shadows on the light bands. Using Super XX film, good results were obtained with an aperture opening of f/32 and slit widths of 0.026 inches. These settings also insured good sharp images. Other types of film of higher contrast and greater resolution have been tested. Records obtained with such film were not as good as those obtained with Super XX because the lower sensitivities required larger apertures and light slits. A data summary of the range is given in Table 1. These values for the apparatus are those ordinarily used for routine records and do not represent rigid parameters.

15. <u>Range Operation.</u> So far the various components of the range and their designs have been considered, but their combined operation and supporting equipment such as power supplies have not been discussed. These equipments shall not be described in detail since they are standard. Their use in the system will be given to show the operation of the range. A block diagram of the range components is shown in Figure 6 to give general arrangements.

16. Preliminary to firing, the circuits are checked for functioning; the camera is loaded with film; the charge is suspended in the bombproof and armed with the detonator; the power supplies are energized; and finally the safety switches just outside the bombproof wall and at the control stations are closed to fire position. At time of firing the camera drum motor is energized and when it reaches full speed the charge is detonated. Pressing the FIRE switch initiates the following sequence of events:

(a) A solenoid switch on the camera shutter opens the shutter and closes the synchronizing micro-switch. The shutter is set at 1/50 second opening.

(b) The synchronizing micro-switch energizes a vacuum switch coil and the vacuum switch closes the circuits to pulse the detonator with a 6000 volt pulse and to trigger a thyratron switch which passes a 6000 volt pulse through a 1:2 pulse transformer to the third electrodes of the flash tubes causing them to flash.

(c) The fragments from the exploding case pass between the lighted slits and the camera and their images are recorded as shadows on the film.

Timing must be controlled in terms of milliseconds. The shutter operation of the synchronizing switch assures that the shutter will be open at the proper time. The essentially simultaneous pulsing of the detonator and flash tubes assures that the flash tubes will be lighted when the fragments pass the slits. No other efforts need be taken to see that synchronization occurs.

GEOMETRICAL CONSIDERATIONS

17. As has been noted previously, only two slits are necessary for velocity determinations. The third slit is needed for identification purposes, and so may be used to obtain a second velocity reading. It turned out that although the distances of separation between slits 1 and 2 and between 2 and 3 were in the ratio of 2:1, the distances between images produced by these slits were in a ratio less than 2:1. This would indicate an appreciable acceleration of fragments, which is not possible at a location some 9 feet from the point of detonation. Therefore, a complete re-examination of the geometry of the range was made: the results are of sufficient importance to be reviewed here.

18. The horizontal plane geometry of the system is shown in Figure 7. Consider a fragment in this figure projected out from the case along path $\overline{BA}$. From the figure, it may be noted that

$$\frac{\overline{BA}}{r} = \tan(\alpha+\phi) , \quad \frac{\overline{AC}}{r} = \tan(\alpha+\phi-\theta) ,$$

and therefore for any point q along the fragment path

$$q = \overline{BA} - \overline{AC} = r\left[\tan(\alpha+\phi) - \tan(\alpha+\phi-\theta)\right] . \qquad (1).$$

It may also be noted that

$$\frac{\overline{HK}}{R'} = \tan\phi , \quad \frac{\overline{JK}}{R'} = \tan(\phi-\theta) ,$$

$$R' = R'' - 2 \text{ (in feet)} .$$

Therefore, the projection q' of q on the slit box face is

$$q' = \overline{HK} - \overline{JK} = R'\left[\tan\phi - \tan(\phi-\theta)\right] . \qquad (2).$$

Expanding (1) by trigonometric identities, we have, eventually, by (2)

$$q = \frac{r}{R'}\left[\frac{q' \sec^2\alpha}{(1-\tan\alpha\tan\phi)(1-\tan\alpha\tan(\phi-\theta))}\right] \qquad (3).$$

Since $$\frac{q'}{R'} = \tan\phi - \tan(\phi-\theta)$$

(3) becomes
$$q = \frac{r\sec^2\alpha}{R'(1-\tan\alpha\tan\phi)}\left[\frac{q'}{1-\tan\alpha\tan\phi + (q'/R')\tan\alpha}\right] .$$

The true velocity of the fragment, (dq/dt), is given by

$$\frac{dq}{dt} = \left[\frac{r\sec^2\alpha}{R'\left(1-\tan\alpha\tan\phi + (q'/R')\tan\alpha\right)^2}\right]\frac{dq'}{dt} , \qquad (4).$$

where (dq'/dt) is the apparent fragment velocity along the slit box face. The acceleration is given by

$$\frac{d^2q}{dt^2} = \left[\frac{r\sec^2\alpha}{R'(1-\tan\alpha\tan\phi+(q'/R')\tan\alpha)^2}\right]\frac{d^2q'}{dt^2} \qquad (5).$$

$$-\left[\frac{2r\sec^2\alpha\tan\alpha}{R'(1-\tan\alpha\tan\phi+(q'/R')\tan\alpha)^3}\right]\left(\frac{dq'}{dt}\right)^2.$$

Because of the geometry of the system, there is an apparent acceleration which is a function of the angle α and the apparent velocity (dq'/dt).

19. Cognizant of this relation, two velocity readings may be obtained from each record, one from fragment travel between slits 1 and 2 and the other from travel between either slits 2 and 3, or slits 1 and 3. Assuming that these are mean velocities at some point q' between the slit pairs, there are two expressions for (dq/dt) in terms of α . The angle α , however, is unknown and only an approximate solution to the velocities (dq/dt) can be obtained. The accuracy of the solutions would not permit observation of any accelerations. Recognizing that α is constant for the two expressions, a fairly good calculation of the mean value of (dq/dt) is possible, but involved. The possibility was suggested of direct measurement of α for each fragment recorded on the film. This value could then be used to compute the true velocity for each slit pair, thereby obtaining the acceleration . There was no difficulty in placing a celotex board at the end of the range, and dividing it into increments to observe α but it was virtually impossible to accurately identify even a small number of the recorded fragments with the record images.

20. It was found, however, that by restricting the value of the angle α (restricting the beam), the maximum error introduced in the true fragment velocity when using the apparent velocity between slits 1 and 3 could be kept less than 0.5 per cent. Velocity determination is only possible, and the middle slit is used solely for identification. From equation (4), the ratio of the true velocity to the apparent velocity may be found as a function of α for different assumed values of q', which are taken as the mid-points between the slit pairs. The resulting family of curves, shown in Figure 8, indicate that for a range of the value of α between 20 and 35 degrees, for q' equal to 15 inches, the maximum variation of the velocity ratio is from 1.017 to 1.022. It should therefore be possible to determine the velocity to within a maximum error of $\pm$ 0.25 per cent of the true value. This figure does not represent the overall accuracy of the range since the error introduced in attempting to select the center of mass of a fragment may be considerably larger. A consideration of the formula giving relative accuracy of measured velocities indicates that these centers of mass must be located to $\pm$ 0.03 inches on the photographic print to assure velocities accurate to 1 per cent. It is believed that this accuracy is attainted. The effect of curvature of the film drum appears on the enlarged

print as a maximum displacement error of 0.002 inches, which is also considerably smaller than the uncertainty in the center of mass determination. It should be pointed out that these simplifications are made possible because of the basic design for the range at ERL, Bruceton. The modifications, as shown, of the principles developed there have resulted in decreasing the design error of the basic range from 2 per cent to 0.25 per cent.

VELOCITY COMPUTATION

21. To illustrate the use of the range, the method of reduction of data is given as an example. The following range constants are used:

S = Horizontal distance between slits 1 and 3 (2.50 ft)

H = Slit height (1.50 ft)

l = Length of film or drum circumference (99.5 cm)

At the time of firing, a measurement is made of:

F = Frequency of drum rotation (rps)

From the film a measurement is made of:

h_f = Slit image height (cm)

A print at a convenient magnification is then made of the film record, and the following measurements made from the print:

H = Slit image height (cm)

X = Horizontal distance between fragment image at slit 1 and at 3. This distance is taken as positive if the fragment velocity exceeds the matching velocity and minus of the fragment velocity is less than the matching velocity.

Y = Vertical distance between fragment image at slit 1 and at 3.

A calculation is then made of

$m = h_p/h_f$, magnification from film to print

$M = H/h_p$, magnification from print to slit size

$V_f = lF$, film drum velocity (cm/sec)

$V_p = mV_f$, drum velocity scaled to print size (cm/sec)

The apparent fragment velocity is calculated from

$$V_a = \left[\frac{V_p \delta}{(S/M) - X}\right] \cdot \left[1 + \frac{Y^2}{(S/M)^2}\right]^{1/2} \quad \text{(ft/sec)}.$$

For values of the trajectory angle α between 20 and 35 degrees the calculated velocity is

$$V_c = 1.0186\, V_a \quad \text{(ft/sec)}.$$

Figure 9 is a typical print from which the data is read. This computation gives the horizontal component of the fragment velocity. An adjustment for the vertical component is made by taking into account the travel in the vertical plane. The velocity associated with each fragment becomes ($V = V_c/\cos\theta$) where θ is the angle the fragment path makes with the horizontal.

SUMMARY

22. The modified velocity range has been in operation for some time and as a direct consequence of the increased image clarity the velocity determinations have been greatly facilitated. Each shot gives on the average fifteen velocity readings and although a larger number may be preferable, this number should give a reasonable valid mean. Image coincidence and difficulty in associating together the images of each fragment more or less limits the maximum number of usable velocity determinations to fifteen to twenty. Another limitation imposed is the length of available flash tubes which in turn limits the useful vertical beam. However, this is relatively unimportant for cylindrical cases, in that the beam is narrow and symmetrical so that a good measure of the fragmentation is obtained. The present system does yield more information about the individual fragments; viz., the size, a better approximation of the presented area, and how this area changes with fragment travel. Although this information has not as yet been utilized, it is of

value in retardation studies which, as has been indicated, are not possible with the present set-up. Shock waves associated with the individual fragments have also been observed, particularly when the film speed was approximately one half the fragment speed. Information from this observation is also as yet unused.

23. Possibilities for future improvements on the existing facilities include: a) locating another camera in such a position as to give more information on fragment profile and on the trajectory angle, b) additional slits which may also be used, either by enlarging the slit box to accommodate more flash tubes or by the use of reflected light and virtual slits. From these slits, it may be possible to obtain a sufficient number of exact simultaneous equations to determine the angle numerically. At the present time, no definite steps have been taken to incorporate these modifications in the range. It is planned, eventually, that the range described above shall be a part of a multistation range of similar principle which will be utilized to study fragment retardation.

TABLE I

RANGE SPECIFICATIONS AND DATA SUMMARY

CAMERA:

Distance, optical center of lens to slit box: 21.78 ft.

Lens: 12 in, f/7

Drum Circumference: 99.50 cm.

SLIT BOX:

Light Source:	G.E. FT-422, 3000 mfd @ 480 V.
Slit Spacing:	#1 to #2, 20 in. #2 to #3, 10 in.
Slit Width:	0.026 in. approximately.
Slit Height:	18.0 in.

Trajectory Angle: 20 to 35 degrees.

TYPICAL DATA:

Drum Speed:	59.9 rps.
Lens Aperture:	f/32. Shutter: 0.02 sec.
Film:	35 mm Super XX, unperforated.
Developer:	Kodak Microdol, 20 min @20°C.

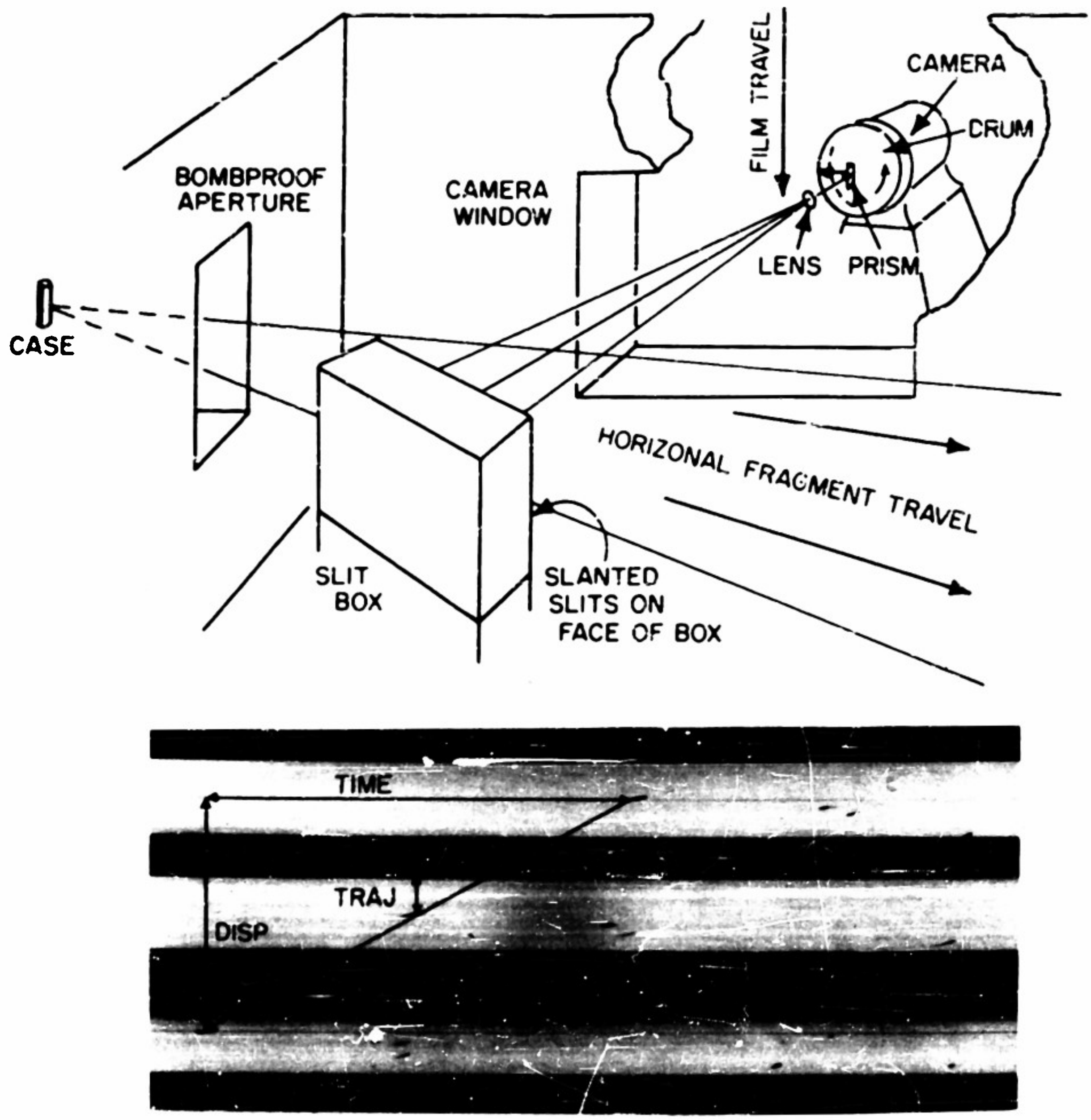
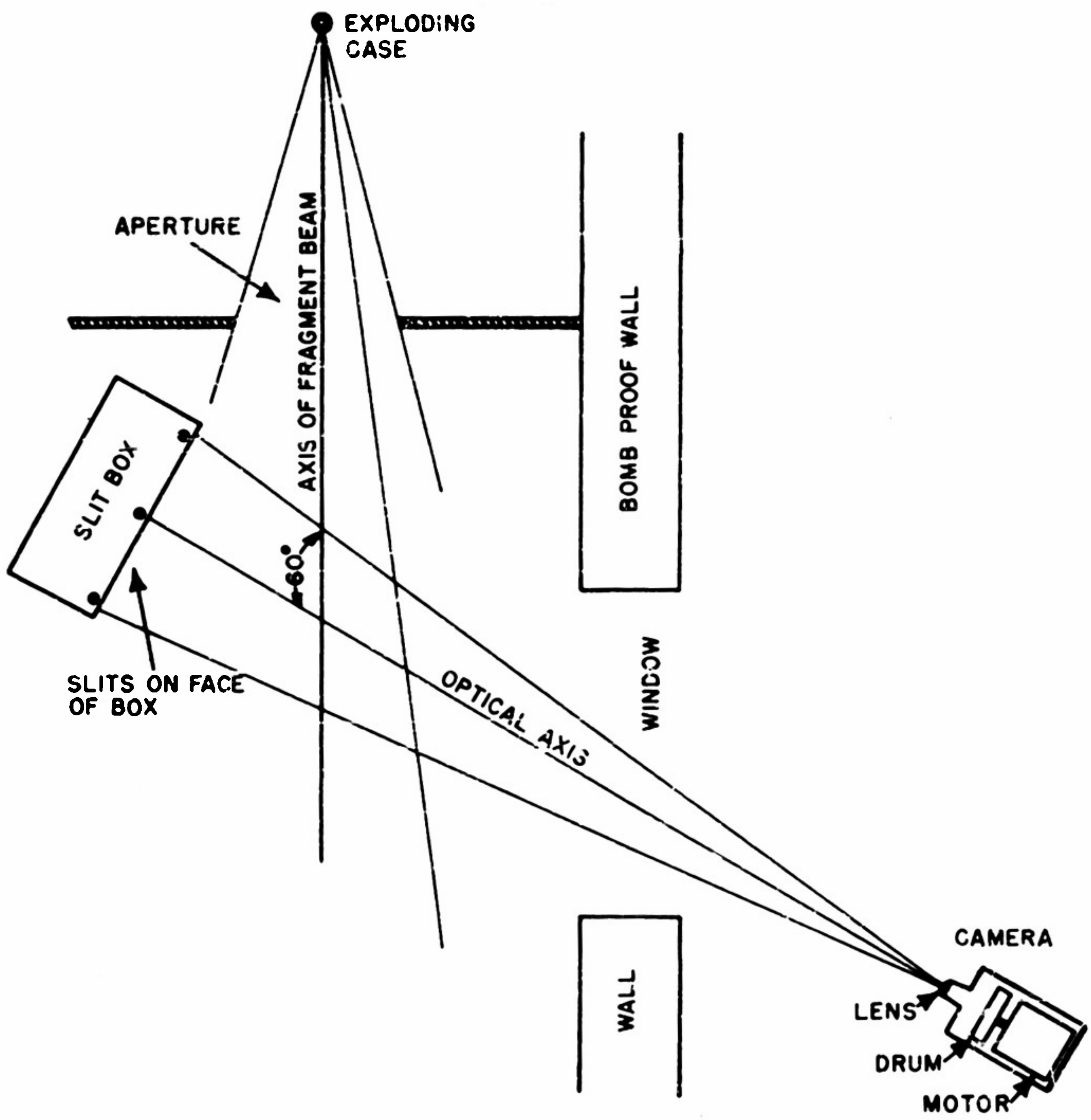


FIG. I THE ERL SYSTEM AT NOL AND A TYPICAL RECORD



F.G. 2 PLAN VIEW OF RANGE GEOMETRY

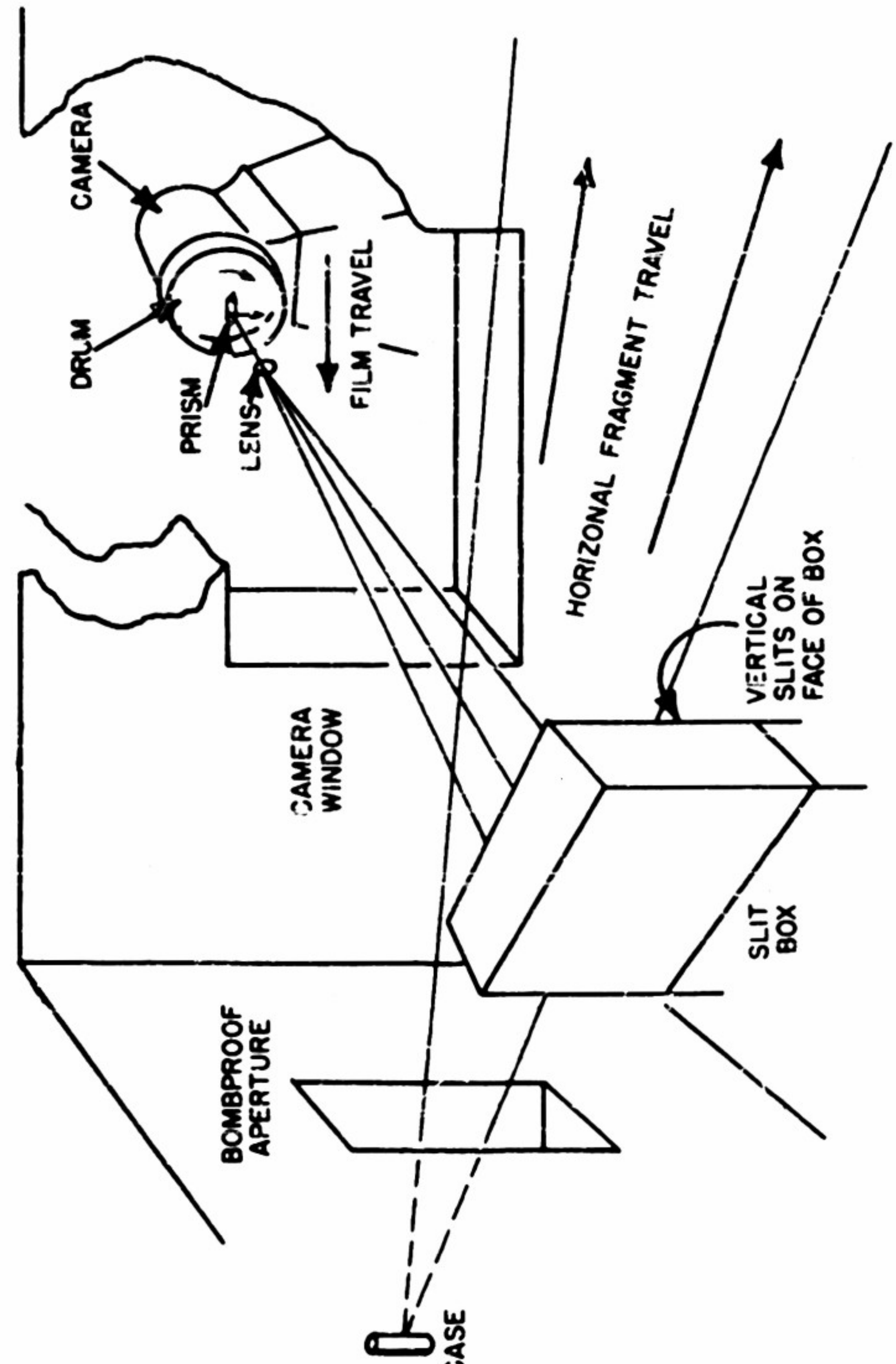
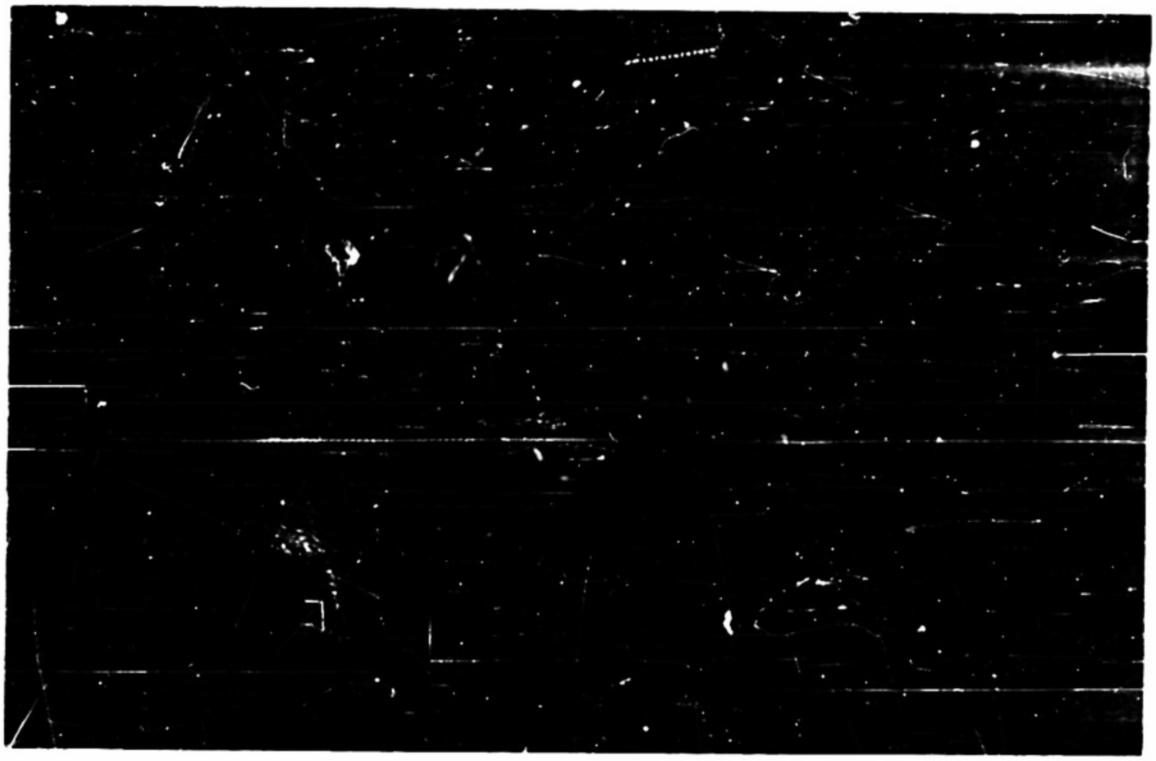
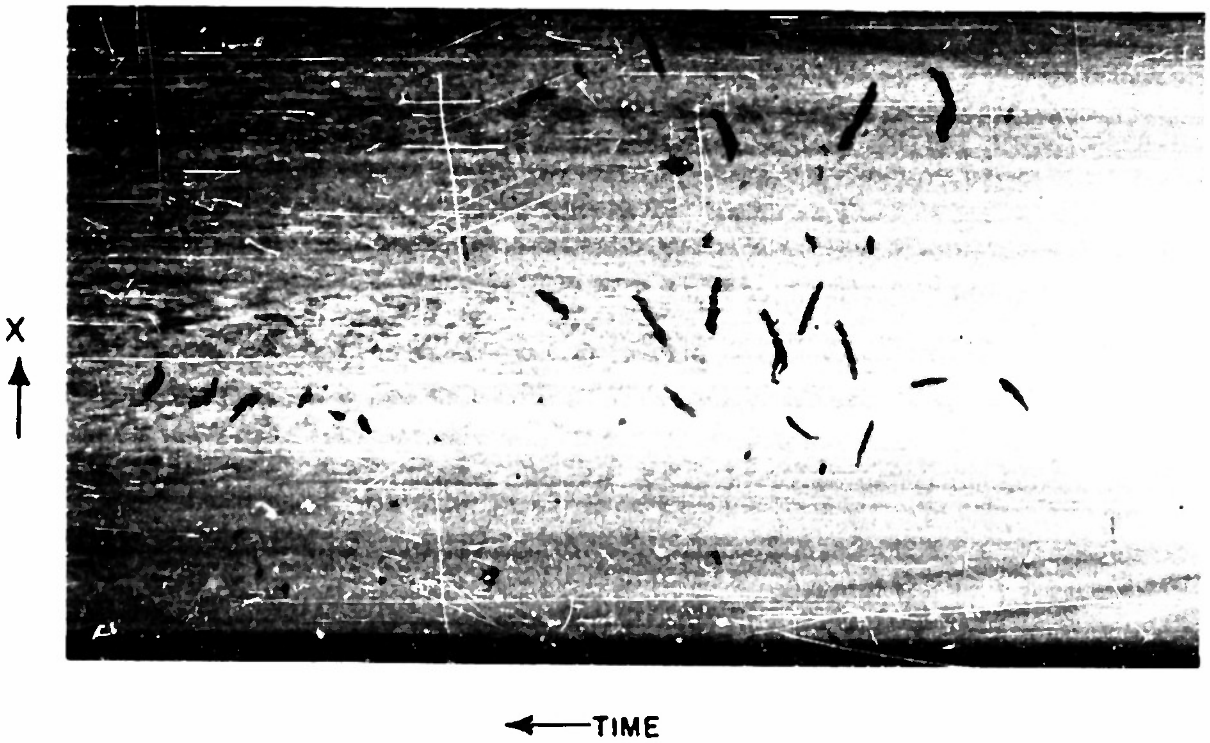


FIG. 3 THE VERTICAL SLIT–ROTATING DRUM CAMERA SYSTEM WITH FILM AND FRAGMENT VELOCITIES MATCHED

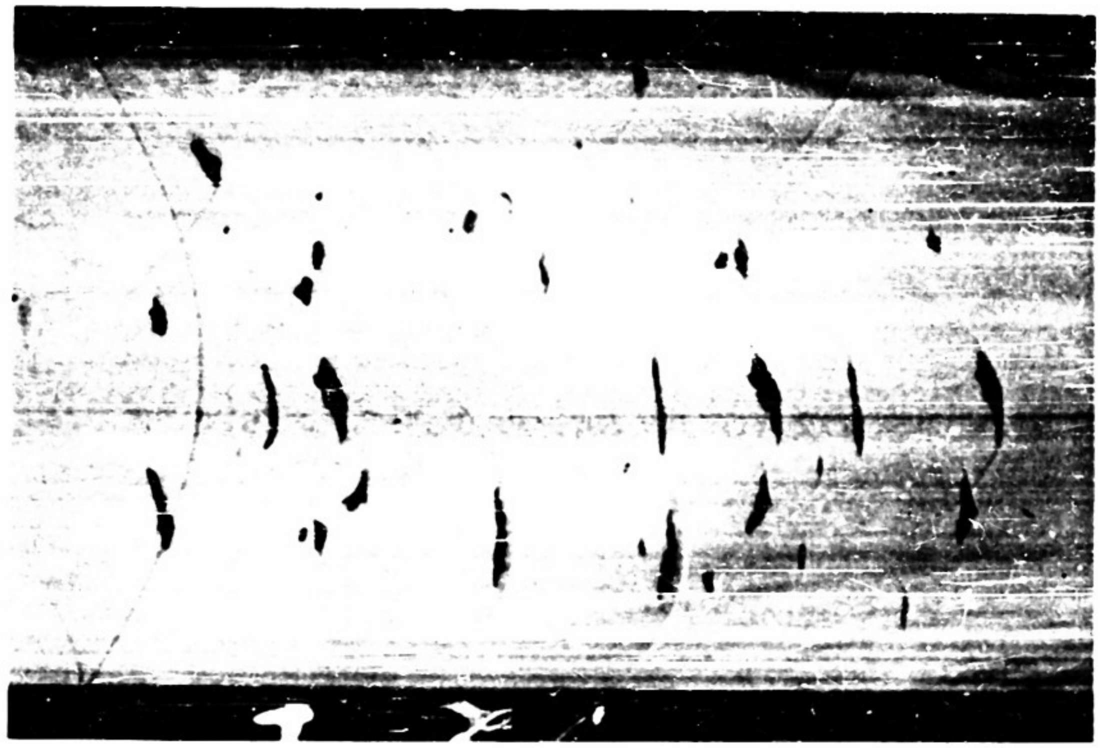


(a) FRAGMENT FRAGMENT ILLUMINATION

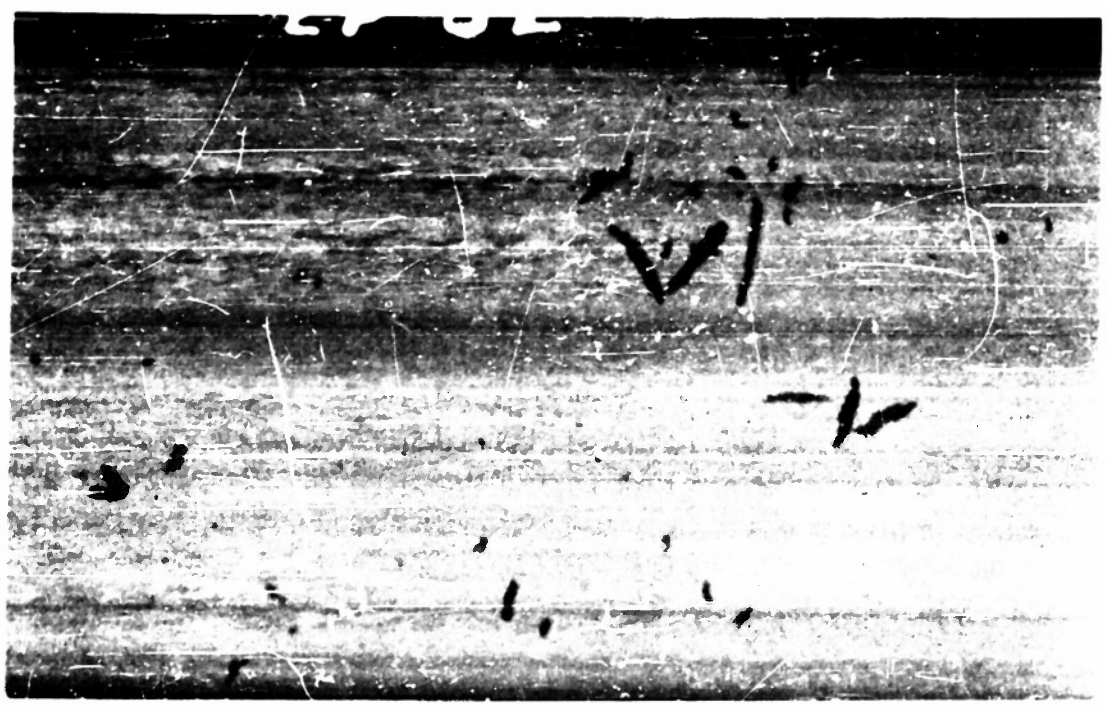


(b) FRAGMENT SILHOUETTE

FIG. 4 TYPICAL RECORDS USING DIRECT AND SILHOUETTE ILLUMINATION



(a) FILM VELOCITY MISMATCHED



← TIME

(b) FILM VELOCITY MATCHED

FIG. 5 TYPICAL RECORDS WITH 12 IN. LENS FOR MATCHED AND MISMATCHED FILM VELOCITIES

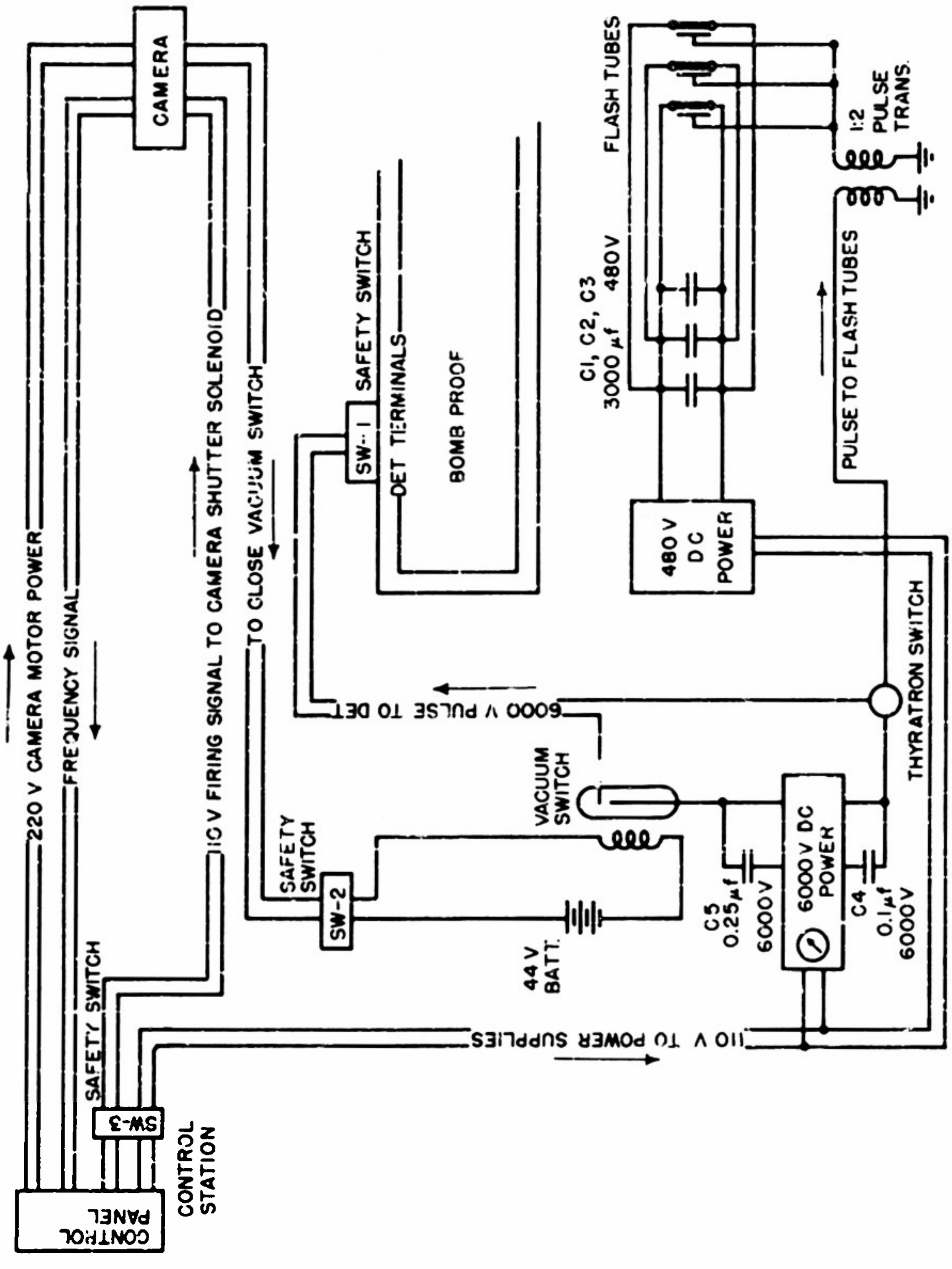


FIG. 6 BLOCK DIAGRAM OF RANGE COMPONENTS

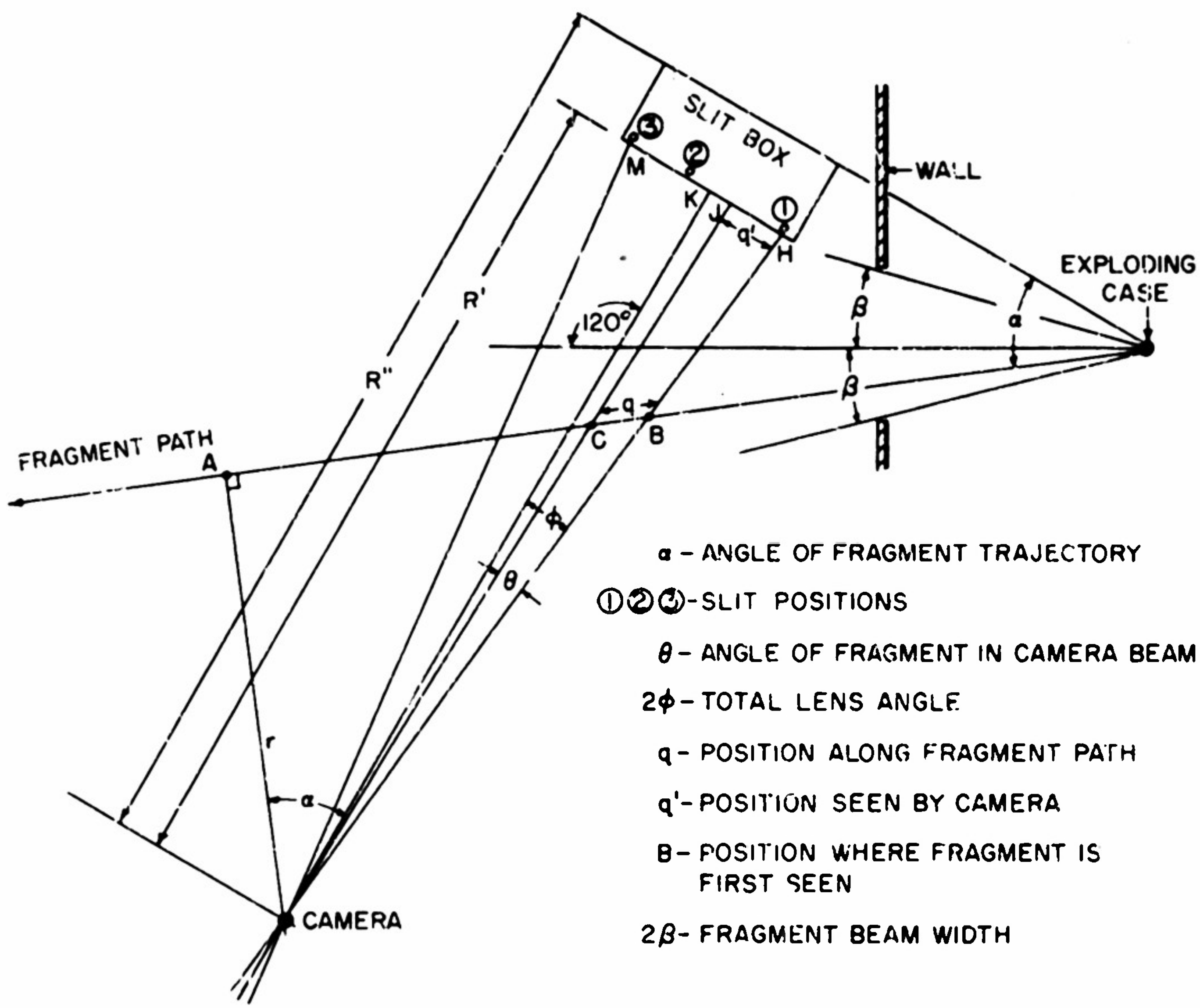


FIG. 7 GEOMETRIC ARRANGEMENT OF FRAGMENT VELOCITY RANGE

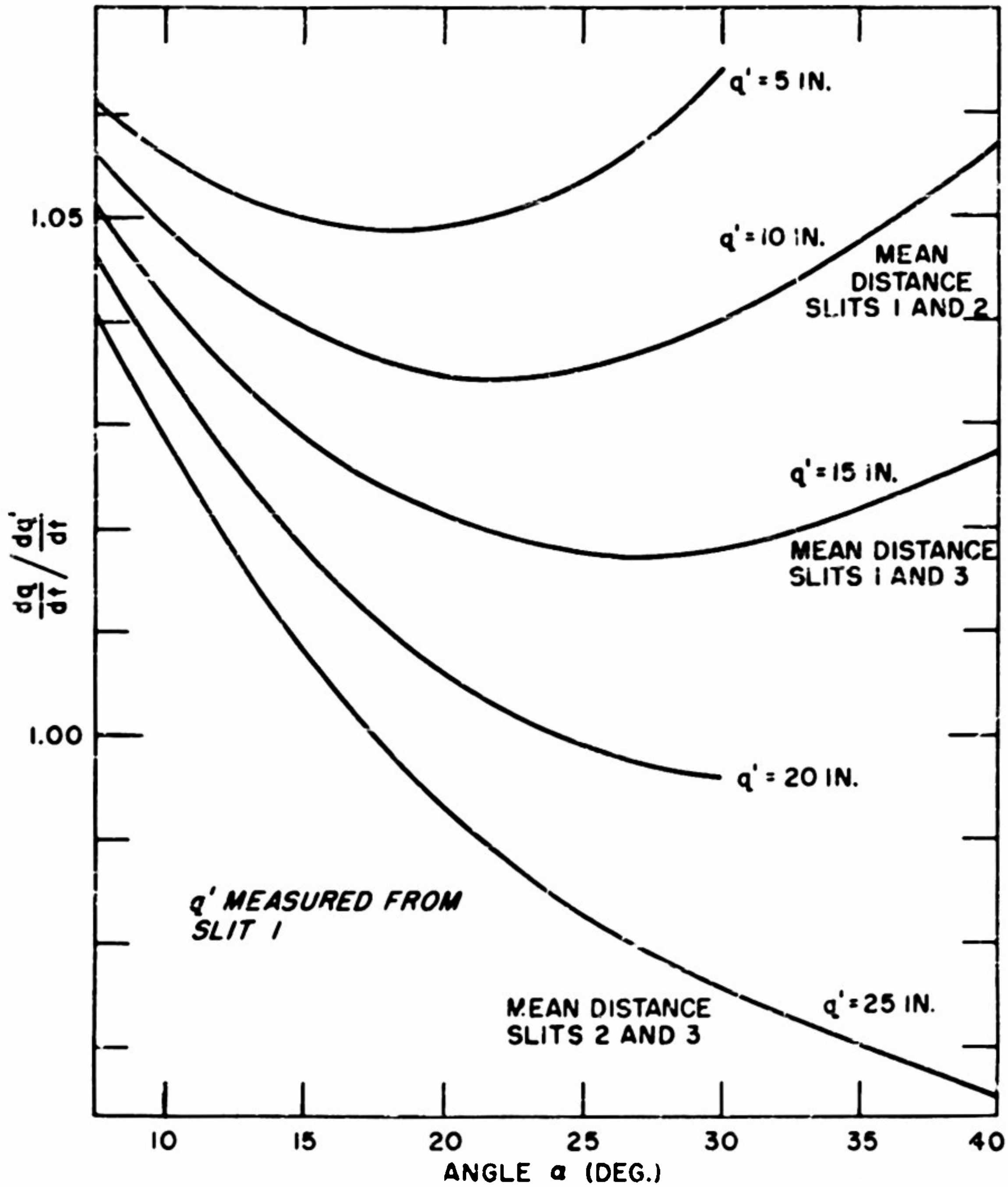


FIG. 8 RATIO OF TRUE VELOCITY TO APPARENT VELOCITY VS FRAGMENT TRAJECTORY ANGLE FOR VARIOUS VALUES OF SLIT SEPARATION

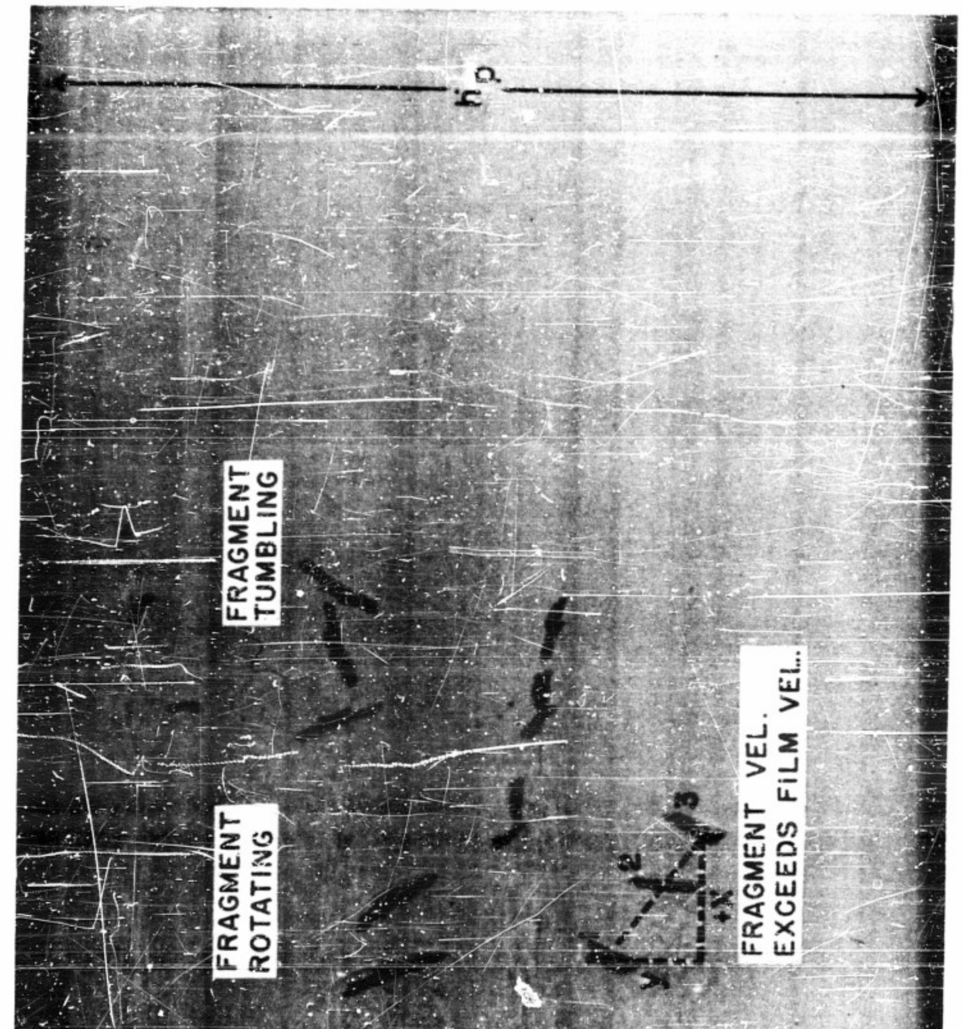


FIG. 9 A TYPICAL VELOCITY RECORD SHOWING METHOD AND DATA NECESSARY FOR COMPUTING VELOCITY.

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